B-Physics at Fermilab

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Introduction

Fermilab has earned a niche in the history of B-physics with the discovery of the b quark in 1977 [1]. Since that time not much has been seen of it at Fermilab until quite recently, where it has been reported in both fixed target and collider experiments.

The fixed target experiments can be broken up into two broad categories: those concentrating on the physics of "heavy" quarks which ostensibly implies charm, including beauty only as a small component of a broad program, and those experiments which boldly and blatantly go after beauty. In the context of their ultimate mission, the current runs of the dedicated beauty experiments can be considered "engineering" runs as they begin to confront the problems inherent to fixed target B-physics. The fixed target experiments reported on in this paper are listed in Table 1.

Table 1. Fixed Target Experiments at Fermilab with Potential for B-Physics.

E-769	250 GeV/c p-nucleon Collisions
E-791	Studies of Heavy Flavors (500 GeV/c π)
E-672	Inclusive J/ψ Production via 530 GeV/c π^-
E-653	Hadronically Produced Heavy Flavor States
E-771	Beauty Production Associated with Dimuon Production in 800 GeV/c Interactions
E-789	Production and Decay into Two-body Modes of B-quark Mesons and Baryons

Of the two collider experiments at Fermilab, D0 has just started running, and most of the CDF B-physics results from the last run have been extensively reported on [2]. John Butler has discussed the most recent results in his talk at this conference [3]. Therefore, most of the discussion of collider experiments will be limited to contrasting their ultimate potential with that of the current and future fixed target experiments.

The list of B-physics topics is extensive and the potential rewards are incentive enough to fuel ambitious attempts to overcome the inherent experimental difficulties of the subject. The near term (mid 1990's) physics goals include measurement of differential cross sections in the energy range of $\sqrt{s}$ = 22 - 42 GeV for fixed target experiments and up to 1.8 TeV at the collider. The lower end of the energy range coincides with the threshold of an accessible cross section and provides a testing ground for perturbative QCD, within the limitations, of course, of the current theoretical uncertainties [4]. Measurements of the B^+ and B^0 lifetimes with less than 5% statistical errors are expected, along with initial measurements of the lifetimes of other states. Spectroscopy of the B_s and baryons with perhaps a chance at the B_c is possible, as well as studies of the relative branching fractions of weak decays. Tagging studies, which would look at exclusive decays, tagging efficiency, signal dilution and semi-inclusive states are important parts of the program as a way to develop techniques for obtaining loftier physics goals in the future. During this period one could begin to observe rare decays such as $B^+ \to K\mu\mu$ and to set limits on others, for example $B^0 \to \mu\mu$, $e\mu$. One can also expect to see the first limits on B_s mixing [5]. To improve and expand beyond the above list of measurements will require a new generation of experiments specifically designed for B-physics. This is particularly true for CP violation, the holy grail of B-physics.

Fixed Target Experiments

Charm was discovered simultaneously in a fixed target and an $e^+ e^-$ collider experiment. Virtually from the moment of discovery, however, the investigation of charm physics was dominated by the $e^+ e^-$ machines, until Fermilab experiment E-691. The high-statistics measurement of charm production in fixed target experiments was made possible largely by the development of two new strategies: the use of silicon vertex detectors, which enable the reconstruction of secondary vertices, and parallel processing technology, which was necessary to handle the huge amounts of data produced by experiments running at high rate with fairly loose triggers. Fixed target B-physics experiments currently find themselves in a situation similar to that of the early fixed target charm experiments, namely, attempting to make viable contributions in a sport dominated by the $e^+ e^-$ machines.

While the fixed target B experiments are faced with many problems, production rate is not one of them. The relatively small $b\bar{b}$ cross section, down by 10^3 compared to $c\bar{c}$, can be compensated for by easily attainable proton intensities. For example, at an intensity of 10^6 - 10^7 interactions/sec, 1-10 X 10^7 $b\bar{b}$ could be produced over a run of 10^7 seconds. Some experiments are anticipating attempts to run at rates greater than 10^8 interactions/sec, which could yield 10^5 $b\bar{b}$'s/hour! Still, running at these proposed rates is not trivial and there are additional problems to overcome. The branching ratios to reconstructable modes are small. A typical example is ψK^*, where the ψ decays to $\mu\mu$, with a branching ratio of 10^{-5}. The small ratio of $\sigma_{b\bar{b}}$ to σ_{tot} and the presence of spectator partons and their fragmentation products generates large backgrounds. The combination of these problems means that fixed target B-physics experiments must have highly selective triggers, which rely on excellent detector performance. A successful B experiment will need all the tricks used by the charm experiments plus new techniques as well.

The general approach of the current fixed target experiments uses some or all of the following techniques:

triggers based on single muons and/or pairs,

on/off line reconstruction of J/ψ,

vertexing used to identify the secondary vertices and eliminate secondary interactions downstream of the target,

on-line. event reconstruction.

E-769

E-769 is a study of heavy flavor produced in 250 GeV/c hadron-nucleon collisions. By analyzing the P_T spectrum of electrons in the region $2 < P_T^2 < 10$ $(GeV/c)^2$ this experiment has recently produced a very preliminary $b\bar{b}$ cross section of approximately 30 nb [6].

E-791

E-791 is a continuation of a series of experiments, E-691 and E-769, of the study of heavy flavor production at the Tagged Photon Laboratory. The general goals of the experiment include production and decay of charm and production of beauty. This experiment currently has on tape 20 billion "minimally biased" events generated by 500 GeV/c π^- on P_T and C targets. They expect to reconstruct more than 200,000 charm events and an as yet unknown number of beauty events. Figure 1 shows some of their preliminary charm signals [7].

E-672

E-672 is a study of inclusive J/ψ production via 530 GeV/c π^-. The experiment consists of muon triggering and analysis in combination with the vertexing and charged particle tracking provided by the E-706 apparatus upstream. The detectors of both experiments are shown in Figure 2. The acceptance for $x_F > 0$ peaks at around $x_F = 0.30$ and the P_T acceptance for J/ψ is flat out to 3.5 GeV/c. A μ pair trigger in conjunction with a fast processor

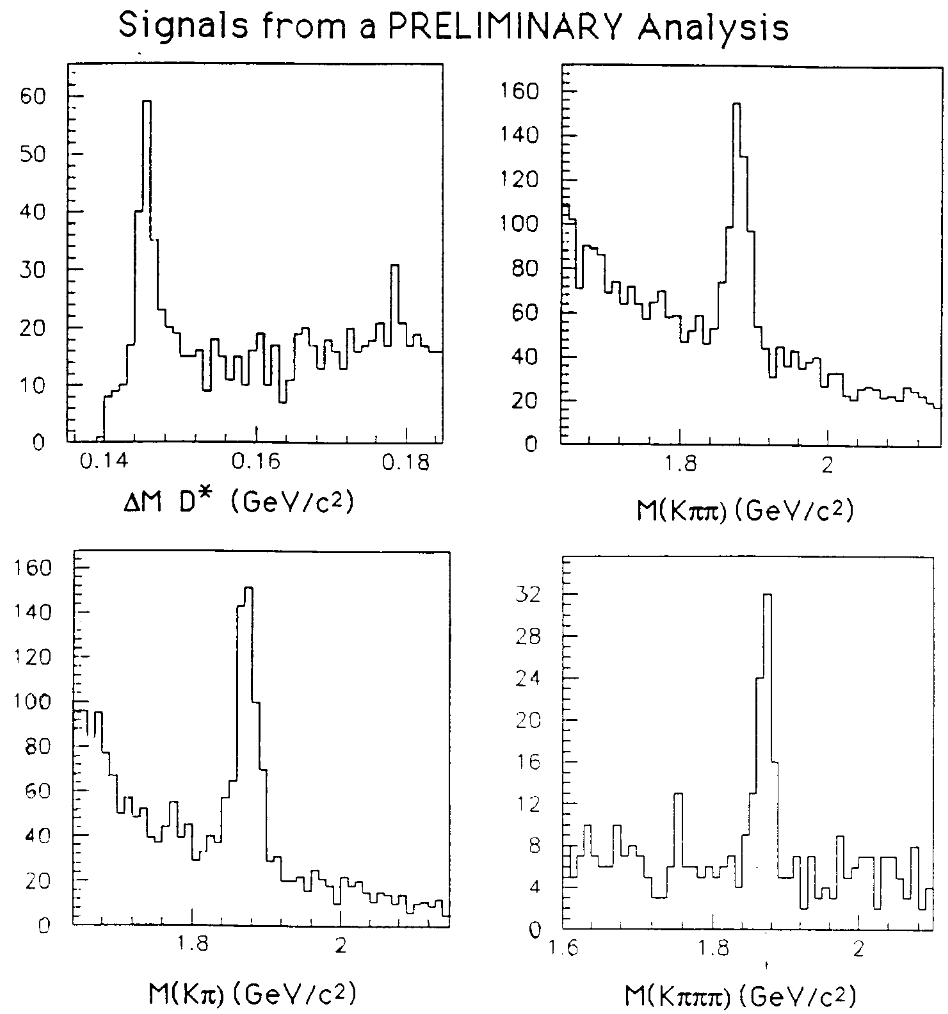
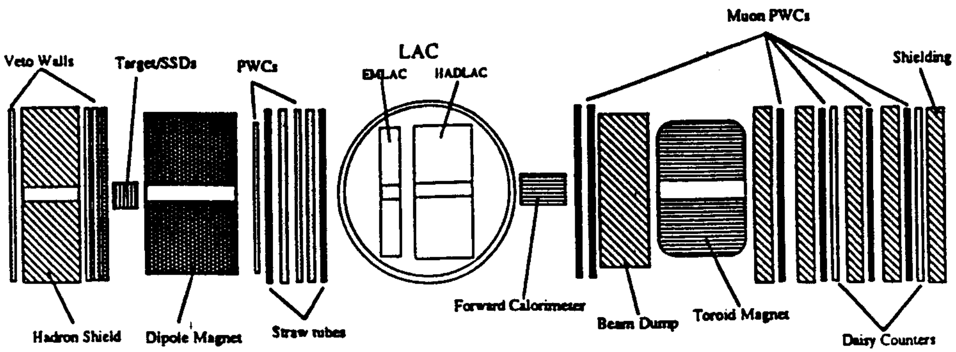


Figure 1. Charm Signals from a Preliminary Analysis of E-791 Data.

E-706/E-672



E-706	E-672
16-plane SSD	Muon Detector -
Charged Particle Spect.	PWC's
LAC	Scintillation Counters
Forward Pb-Glass	Toroid Magnet

Acceptance:

μ pairs for $x_F > 0$ w/ peak at $x_F = 0.30$

Flat in P_T for J/ψ with $P_T < 3.5$ GeV/c

Figure 2. E-706/E-672 Spectrometer.

to calculate the effective mass of track combinations generated a sample of 13 X 10^3 reconstructed $J/\psi \rightarrow \mu^+\mu^-$. J/ψ's emerging from a secondary vertex were used to tag B's, which for this mode have a branching ratio of 1.12%. The simplicity of a muon pair trigger and the clean reconstruction of the J/ψ offset some of the disadvantages of the small branching ratio. In addition, $B \rightarrow J/\psi X$ includes many modes with all charged final states allowing full reconstruction and hence, direct lifetime and mass measurements.

The primary background comes from J/ψ's produced in secondary interactions downstream of the primary vertex. A series of clean-up cuts were imposed as a means of identifying events with secondary vertices and reducing the number of events containing secondary interactions. These cuts reduce the final event sample to 73 events. The experiment used a thick target and as a further measure to reduce the background from secondary interactions, only events with secondary vertices at least 6σ away from material-free gaps in the target were accepted. Figure 3 shows the distribution of secondary vertices in the material free regions around the target. With background estimates this experiment reports a preliminary signal of 9 ± 4 secondary vertex J/ψ events from B decays in the material free regions. The experiment is now working on an estimate of $\sigma_{b\bar{b}}$.

The sample of 73 events was then examined for evidence of exclusive B decays with a J/ψ in the final state. The significant channels are $B \rightarrow J/\psi K$ and $B \rightarrow J/\psi K^*$. The $B \rightarrow J/\psi K$ analysis yielded four events. Two of these were consistent with one each of $B^+ \rightarrow J/\psi K^+$ and $B^- \rightarrow J/\psi K^-$. For the second mode, hadron pairs in the K^{0*} mass region were combined with J/ψ tracks in a four-prong vertex fit. In an analysis similar to that for $B \rightarrow J/\psi K$, five events passed the cuts with three in the B-mass region. A combined mass plot is shown in Figure 4 [8].

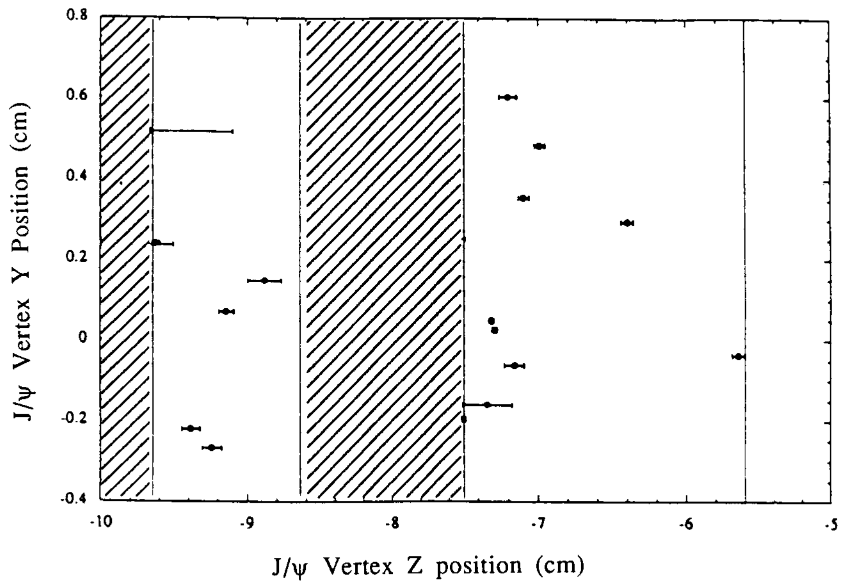


Figure 3. Distribution of Secondary Vertices in Material Free Regions Around the Target.

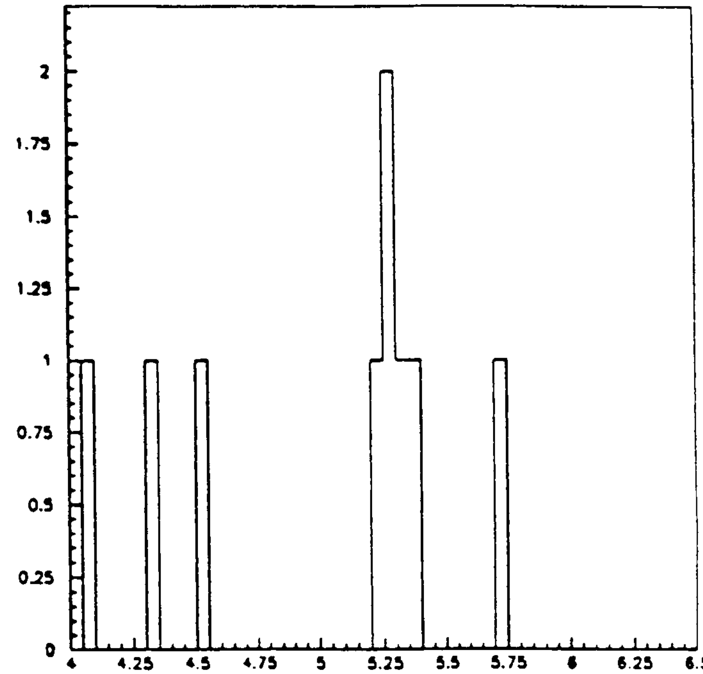


Figure 4. Combined (J/ψ K*), (J/ψ K) Invariant Mass (GeV/c^2).

E-653

E-653 employs a hybrid emulsion spectrometer to study hadronically produced heavy flavor states. A diagram of the experiment is shown in Figure 5. The trigger strategy required a target interaction and a single muon in an attempt to enhance the sample with semimuonic charm and beauty decays. Out of 2.5 X 10^8 interactions, 8.2 X 10^6 events were recorded. The emulsion was scanned for events containing a muon with $P_T > 1.5$ GeV/c. This cut, together with the acceptance of the experiment, imposed an implicit cut on the muon momentum of approximately 20 GeV/c. A primary vertex was found for 6,542 of the high P_T muon events within the fiducial volume. Muons from K and π decay were eliminated by slope matching with primary tracks and impact parameter cuts. These cuts reduced the sample to 359 events containing a μ which did not originate from the primary (μNFP). A series of procedures was undertaken to eliminate secondary interactions in the emulsion, locate vertices outside of the emulsion and match spectrometer tracks with emulsion tracks. The 359 μNFP events were classified kinematically and topologically, yielding the following:

98	muons from interaction,
63	vertex of strange particle decay,
175	vertex consistent with charm decay, (in 122 of these events the charm partner was found),
9	met no criteria for s, c, b,
5	origin of muon not found,
9	met beauty criteria.

The final sample was required to have at least three vertices consistent with $b\bar{b}$ decay and charm cascade decay. The nine beauty events, containing 12 neutral and six charged decays are shown schematically in Figure 6. The estimated background, based on extensive Monte Carlo studies, is approximately 0.3 events in the final sample.

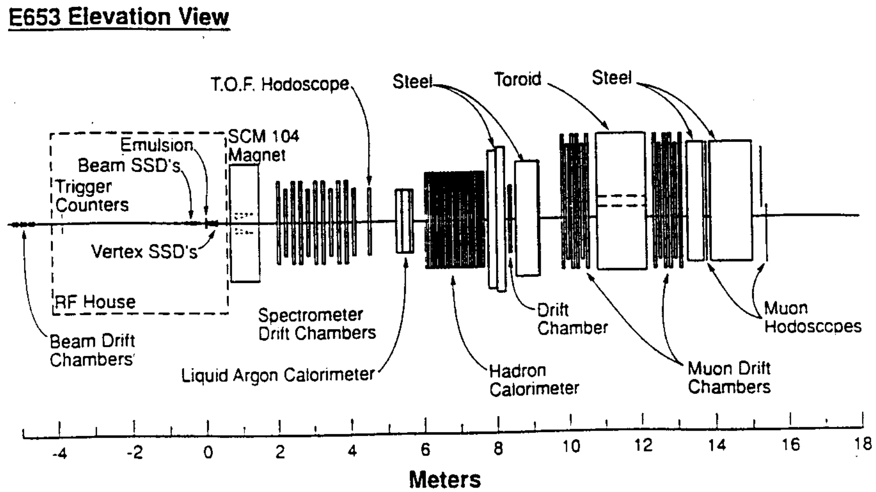


Figure 5. Plan View of E-653 Detector.

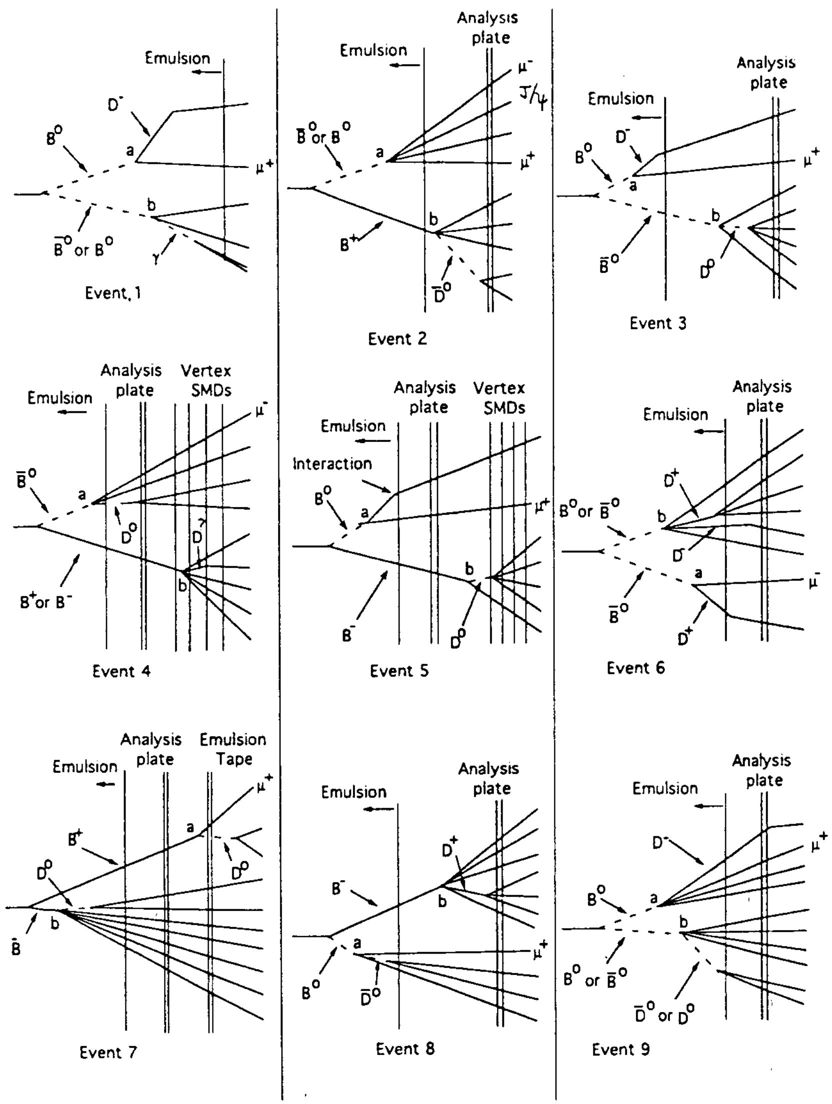


Figure 6. Schematic Representation of the E-653 Beauty Events.

The acceptance of the experiment is quite good although it is biased somewhat for the trigger $b/\bar{b}$. The x_F acceptance for the triggering beauty particle covers the range of $-0.2 < x_F < 0.8$, while for the partner it is $-0.8 < x_F < 1.0$. The P_T efficiency for the triggering beauty particle is enhanced toward high P_T because of the P_T cut on the trigger μ. Using the parameterization

$$\frac{d^2s}{dx_F dp_T^2} \propto (1-|x_F - x_0|)^n \exp(-bP_T^2)$$

the fit gives $n = 4.55^{+2.85}_{-2.05}$ (stat) $\pm$ 0.75 (sys) and

$b = 0.095^{+0.04}_{-0.03} \pm$??? with x_0 fixed at 0.075.

This value of n is similar to an earlier result from this experiment for charm of 4.25. The P_T distribution however, is much stiffer than for charm, due to the larger mass of the b quark.

Based on the nine events, E-653 obtains a preliminary cross section of

$$\sigma_{b\bar{b}} = 33 \pm 11 \text{ (stat)} \pm 7 \text{ (sys) nb/nucleon}$$

for all x_F and assuming A^1. This is about 700 times smaller than the cross section for charm and is consistent with current theoretical predictions [9].

The measured lifetimes for the 12 neutral and 6 charged beauty decays were,

$$t_{b0} = 0.81^{+0.34+0.09}_{-0.22-0.02} \text{ ps} \quad t_{b\pm} = 3.84^{+2.73+1.39}_{-1.36-0.15} \text{ ps}$$

with a combined result of $t_b = 1.86^{+1.13+0.52}_{-0.61-0.02}$ ps.

Momentum estimators were necessary in the case of unconstrained charm and beauty decays with missing or neutral particles. The two methods used agreed with the data sample to within approximately 27%. Distributions of momentum and the proper decay time are shown in Figure 7. The measured neutral lifetime is 1.4 standard deviations below the world average. At a center-of-mass energy of 33.6 GeV it is conceivable that the neutral sample is contaminated with B_s and Λ_b. A composite sample might also explain the excess of neutral B's. On the other hand, the charged B sample is not likely to be contaminated, but the lifetime, dominated by two long decays, exceeds the world average by more than two standard deviations [10].

It was observed that the trigger muon came from the neutral B in all but one case and that none of the events was triggered by a muon from a cascade charm decay. The semimuonic decays all exhibited characteristics expected of beauty, such as low multiplicity and high P_T muons. In all but one case the muon P_T was greater than allowed for charm.

E-789

E-789 is an ambitious attempt to measure the production and decay of B-mesons and baryons. The list of physics goals includes mass and lifetime measurements and tests of weak decay models. The experiment deviates from "standard" approaches to fixed target B-physics in that it focuses on two-body hadronic decay modes with branching ratios of around 0.01%. The primary examples are:

$$B_d \to \pi^+\pi^-,$$

$$B_d \to K^+K^-,$$

$$B_s \to \pi^+ K^-,$$

$$\Lambda_b \to K^+ \pi^-,$$

and $B \to \psi X \quad (\psi \to \mu^+\mu^-, e^+e^-)$.

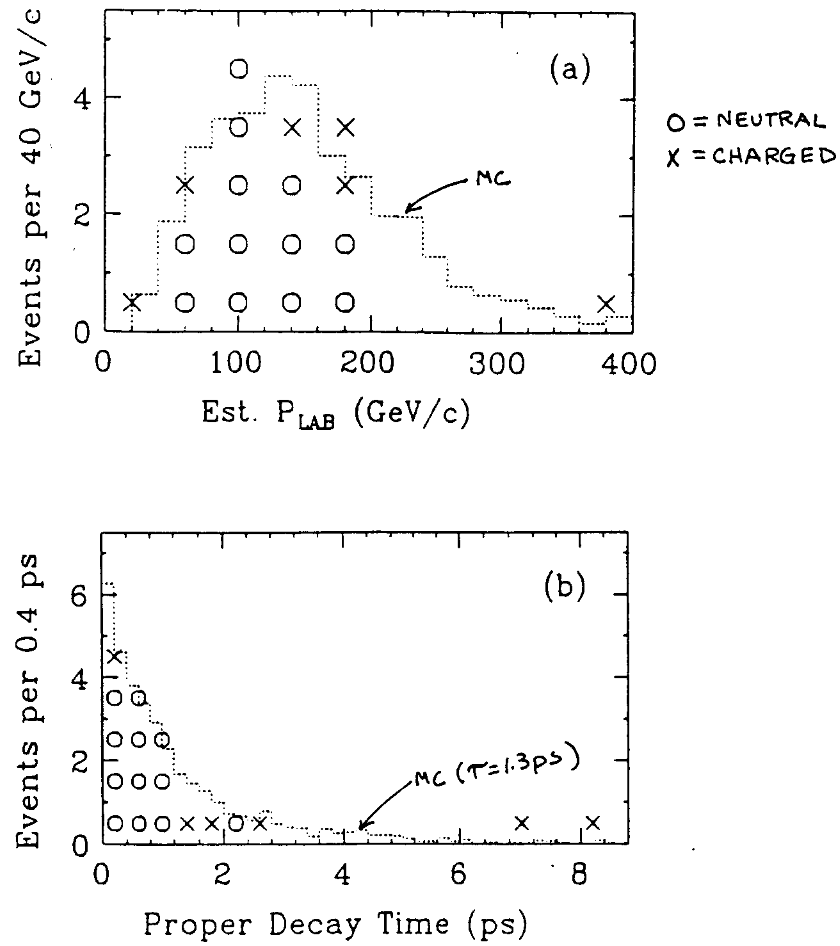


Figure 7. (a) Momentum and (b) Proper Decay Time Distributions of the Charged and Neutral b Events.

The spectrometer features a semi-closed geometry and is tuned to accept high-mass hadron pairs. It is designed to operate at a rate of 10^8 interactions per second. A diagram of the apparatus is shown in Figure 8. The high rate capability is dependent on a ± 6 mm hole in the 16 plane silicon detector system and a wire target, 250 µm X 2 mm, which is less than 10% of a B decay length. The charged particle spectrometer utilizes a large dipole magnet, PWC's, a RICH detector, a muon system, and calorimetry. An on-line vertex trigger processor is used to make impact parameter cuts on PWC tracks [11].

The running period, in which 1.5 X 10^9 events were recorded over 8 X 10^4 beam spills, was divided roughly equally between charm and beauty (two months each). The charm running period was used to tune up the silicon detector and processor on $D \rightarrow K\pi$. A background reduction of X10 was achieved. The experiment expects approximately 4.5 X 10^4 $D^0 \rightarrow K\pi$ events on tape with both Au and Be targets. Beauty running was at a setting which simultaneously optimized the sensitivity to $B \rightarrow J/\psi$ and $B^0 \rightarrow h^+h^-$. The interaction rate during this run was limited by radiation safety considerations. Even so, the experiment ran at 50 MHz interaction rate and generated 2.5 X 10^{13} interactions overall [12].

E-771

E-771 is another of the fixed target experiments dedicated to beauty. Its goal is the study of beauty production and other heavy quark physics associated with dimuon production in 800 GeV/c proton-proton interactions. The principal physics goals are measurement of $\sigma_{b\bar{b}}$, inclusive differential distributions and correlations, reconstruction of exclusive final states, B lifetimes (both inclusive and exclusive) and observation of $B\bar{B}$ mixing. The open geometry detector is capable of 2 X 10^6 interactions per second and is a combination of a conventional spectrometer and an elaborate silicon tracking system, shown in Figure 9. Triggers were generated by either two muons or a single muon with a P_T threshold as determined by an on-line processor. The experiment had three to four good weeks of running in 1991, and conservative estimates predict approximately 12 $B\bar{B} \rightarrow J/\psi \rightarrow \mu\mu$

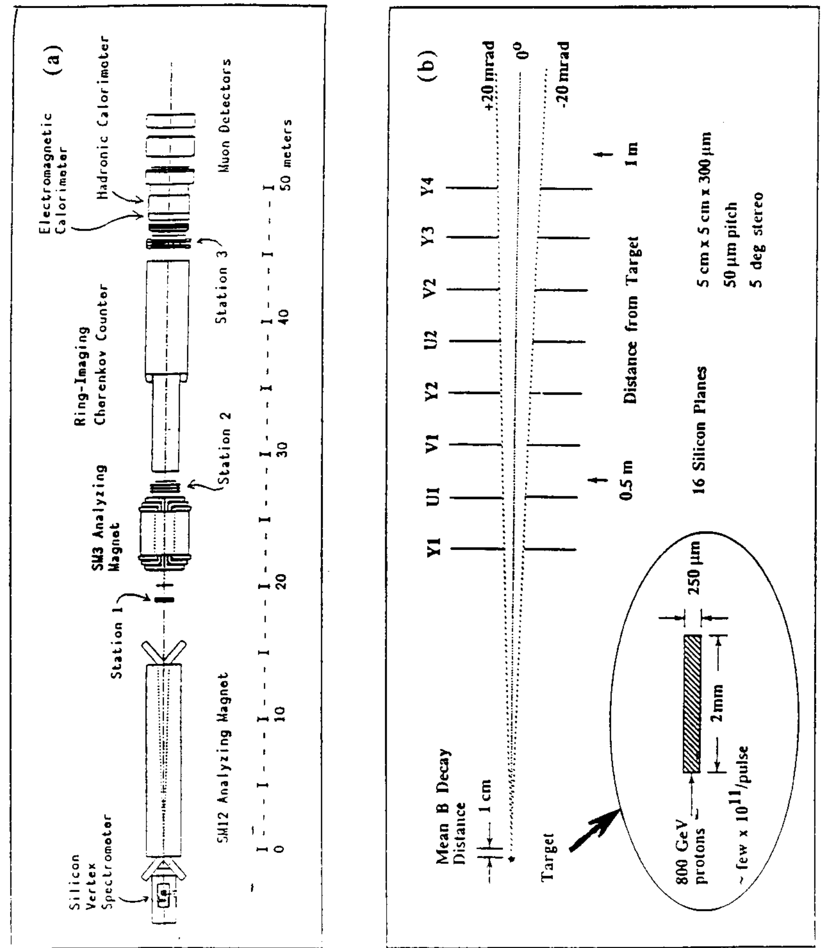


Figure 8. (a) E-789 Spectrometer and (b) Target and Vertex Detector.

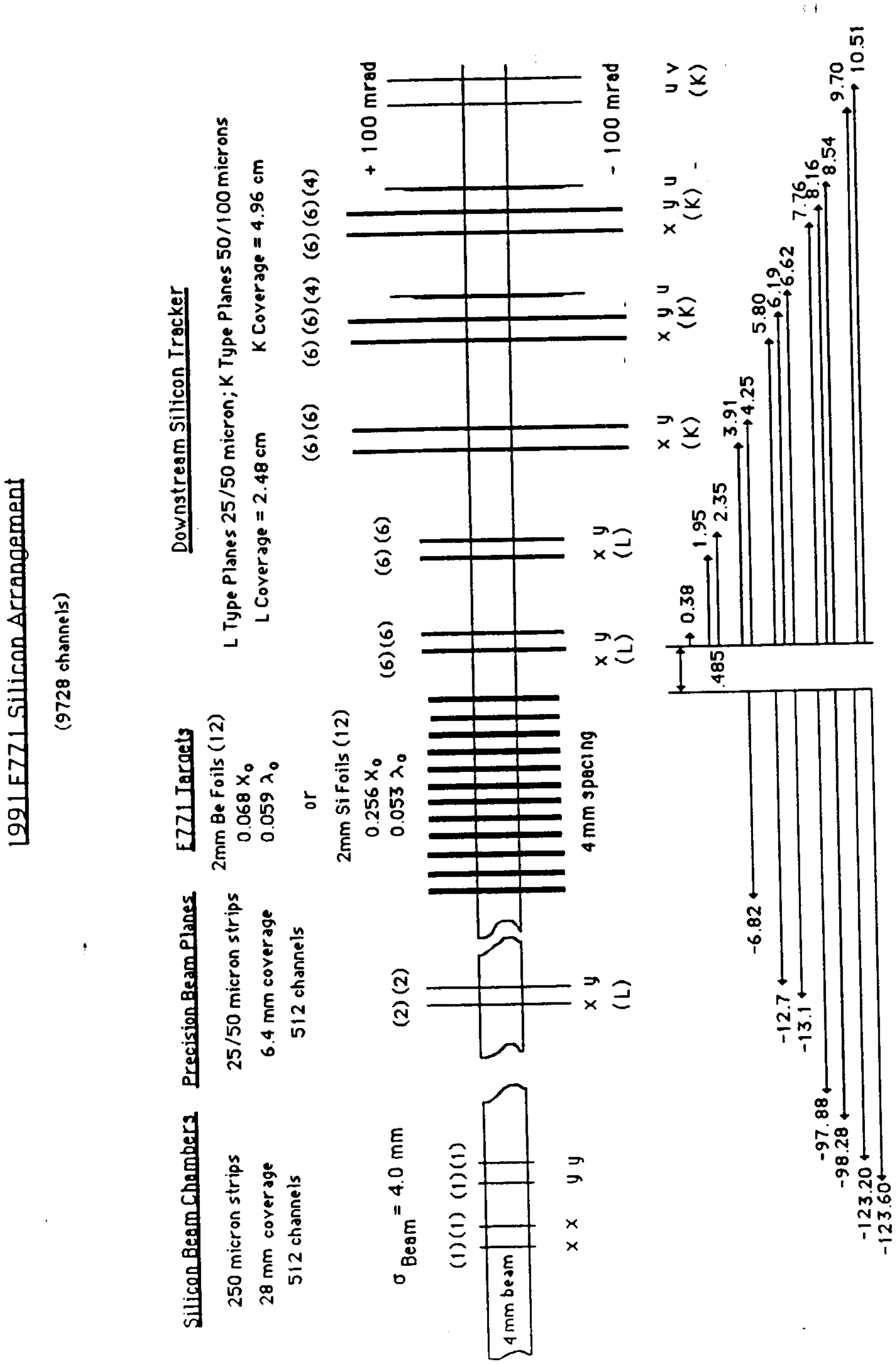


Figure 9. E-771 Silicon Tracking System.

per week for the dimuon trigger and 520 $B\bar{B} \rightarrow \mu + X$ per week for single μ's [13].

Collider Experiments

The cross section for b production is much larger than for fixed target, and the ratio

$$\frac{\sigma(pp \rightarrow b\bar{b}X)}{\sigma(\text{inelastic})} \approx \frac{50\mu b}{60 mb} \approx 10^{-3}$$

is more favorable (comparable to charm). The luminosity and estimated b yields are shown below for the Tevatron and what is expected after the Main Injector upgrade. Clearly, luminosity is not an issue for collider B-physics [14].

	Pre-Main-Injector '92	Main Injector '96
Luminosity	5×10^{30}	5×10^{31}
$b\bar{b}$ in 10^7 s	2×10^{9}	2×10^{10}

The two collider experiments, CDF and D0, are designed for high P_T physics and are not optimally configured for B-physics. This fact has not, however, prevented CDF from doing B-physics. Both detectors are evolving toward more "B-like" experiments via various upgrades, which include revised triggering schemes, increased acceptance and vertexing. The collider experiments are now employing some of the same techniques developed by the successful fixed target charm experiments, modified for use in a new environment.

Future Prospects

Fixed Target Experiments

Several of the fixed target experiments have B-physics on their agenda and both of the dedicated B experiments are making plans for the next fixed target run, though neither experiment has yet been approved.

E-771 will add additional silicon tracking to make a total of 24 planes. A full P_T trigger will be installed and they plan to take data with an interaction rate of 10^7 interactions per second. These upgrades and a longer running period should net a factor of 20 to 30 over the last run, yielding approximately 1000 fully constructed and many more partially reconstructed B's [13].

E-789 will increase the acceptance for $B^0 \rightarrow h^+h^-$ by raising the magnet current and attempt to run at the design rate of 10^8 interactions per second. With increased running time and a beam momentum of 900 GeV/c they expect to achieve a sensitivity of 10^{-5} for two-body decays which would yield approximately 1000 reconstructed decays in five modes. Other upgrade possibilities exist which might increase the sensitivity to 10^{-6} [12].

P-829 (E-791) is a proposal to study heavy quark production and decay with a 500 GeV/c pion beam at the Tagged Photon Laboratory. The primary emphasis will be on charm physics, though some B-physics is anticipated for modes which cascade via $B \rightarrow D \rightarrow K$. The B sample can be enhanced by raising the P_T trigger threshold and should provide measurements of $\sigma_{b\bar{b}}$ and lifetimes with partially reconstructed events [15].

The currently proposed experiments will produce measurements of the rate and dynamics of hadronic beauty production, which can be compared with QCD predictions. Lifetimes and relative branching fractions for rare two-body modes are also topics within the physics reach of these experiments. One should not lose sight of the fact that these experiments, and others like them, can provide valuable experience for the next generation of experiments.

It is clear that fixed target machines can provide a copious source of B's, and future success in fixed target B-physics will depend on the development of new technology in triggering and rate capability, which has interesting parallels with SSC and LHC detector R & D.

Collider Experiments

CDF has demonstrated potential for high-statistics B-physics at the Tevatron collider. The planned upgrades for CDF and D0 will further enhance their B-physics capabilities but they are still essentially "high-P_T" experiments. Dedicated experiments will stress acceptance at lower P_T and in the forward direction.

CDF has implemented several improvements for the current run that will enhance their ability to contribute to B-physics. A silicon vertex detector has been installed, the muon coverage is extended and a lower P_T threshold has been implemented on the μ triggers [16]. Last run, with an integrated luminosity of 4 pb^{-1}, CDF was able to reconstruct 34 ± 9 events in the modes $B^+ \rightarrow J/\psi K^+$ and $B^0 \rightarrow J/\psi K^*$ [2]. Over the current run they will accumulate 75 - 100 pb^{-1}. With a gain of a factor of two for μ coverage and a factor of six by lowering the P_T trigger threshold from 3 GeV → 1.8 GeV, they expect more than 8000 exclusive decays in the two modes. In addition to these two modes, inclusive leptons and inclusive lepton plus charm modes can be used for studies of production and mixing. Possibly several hundreds of $B_s \rightarrow J/\psi\ \phi$ and several tens of $\Lambda_b \rightarrow J/\psi\ \Lambda$ will be reconstructed. Measurements of the B^+ and B^0 lifetimes will be made with less than 5% statistical errors [5]. This is a relatively impressive list of B-physics topics for a high P_T hadron collider experiment.

D0 has no magnetic field, which makes exclusive B-physics very difficult. They do however, have excellent μ coverage out to $|\eta| < 3.6$ which will allow them to make significant inclusive lepton measurements.

Further upgrades are planned by both experiments for the next collider run, scheduled tentatively for 1995. CDF will install new end-cap calorimeters, substantially improving the forward e and μ coverage. The vertex detector will be upgraded for better acceptance of t and b [16]. D0 plans to add a 1.5 Tesla solenoid. A vertex detector of silicon and scintillating fibers will allow vertex reconstruction out to $|\eta| < 3$ [17]. The upgraded detectors will look at rare decays such as $B^+ \rightarrow K\mu\mu$ with limits for $B^0 \rightarrow \mu\mu$, $e\mu$. Limits for B_s- mixing will be possible and spectroscopy of B_s, Λ_b and $B_c \rightarrow \psi\pi \rightarrow \mu\mu\pi$. They of course will uniquely measure the cross section at $\sqrt{s}$ of 1.8 TeV.

There are no existing dedicated collider B-physics proposals at this time. It is envisioned that there will perhaps be one or two runs with the Main Injector emphasizing, as before, high P_T physics with B-physics on the side. Subsequent runs then might have one high P_T experiment and one dedicated B-physics experiment.

Conclusion

B-physics is still in the infant stage at Fermilab. The recent results of the fixed target and collider programs are promising however, and serve as an impetus for further advancement and study. If B-physics is pursued aggressively, it might not be unreasonable to expect challenges to the Standard Model by the end of the decade.

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